The Role of the National Ignition Facility in the Development of Inertial Fusion Energy

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Introduction

We have completed a conceptual design[1] for a 1.8-MJ, 500-TW, 0.35-μm solid-state laser system for the National Ignition Facility (NIF), which will demonstrate inertial fusion ignition and gain for national security, energy, and science applications. Figure 1 shows the size and scale of the facility, which is the minimum size required to achieve inertial fusion ignition. The technical goal of the U.S. Inertial Confinement Fusion (ICF) Program as stated in the current ICF Five-Year Program Plan[2] is "to produce pure fusion ignition and burn in the laboratory, with fusion yields of 200 to 1000 MJ, in support

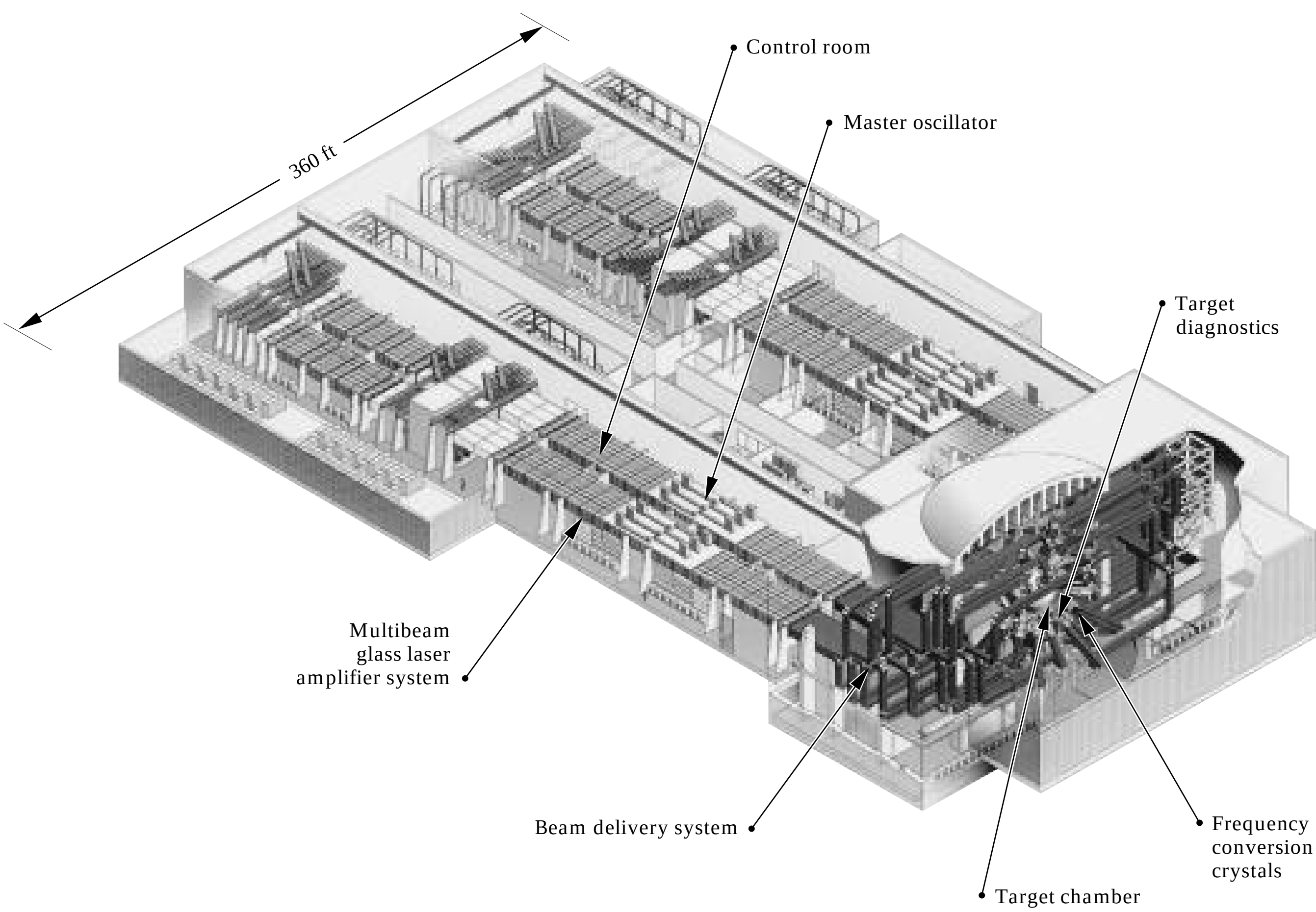


FIGURE 1. The 192-beam National Ignition Facility will demonstrate inertial fusion ignition for defense, energy, and science missions. (40-00-0294-0498Zpb02)

of three missions: (1) to play an essential role in accessing physics regimes of interest in nuclear weapon design...; (2) to provide an above-ground simulation capability for nuclear weapon effects...; and (3) to develop inertial fusion energy for civilian power production.” This article addresses the third goal—the development of inertial fusion energy (IFE).

The NIF plays an important role in IFE development. In October 1994, U.S. Department of Energy (DOE) Secretary O’Leary made the official decision (Key Decision 1, or KD1) to proceed with the NIF. The achievement of inertial fusion ignition, NIF’s primary near-term goal, is a key to developing IFE. In addition, the NIF will provide the means of optimizing the conditions for minimum driver energy, power, pulse shape, and symmetry required to get ignition and gain in a cryogenic deuterium–tritium (DT) capsule. This is the most difficult and important test of the feasibility of IFE with any driver. In fact, the 1990 National Academy of Sciences (NAS) review[3] of the ICF Program recommended glass lasers, as used in the NIF, as the only driver sufficiently mature to proceed with an ignition demonstration facility (i.e., the NIF). The review also noted that ignition in the NIF would be a prerequisite to any future inertial fusion facility, even with other, future drivers.

The development of IFE requires both the NIF and a parallel development program in efficient, high-pulse-rate drivers. The NIF, due to its defense mission, is not required to provide laser pulses more frequently than several hours apart; to produce IFE in future power plants, about 5 pulses per second will be required. In addition to a higher pulse rate, an IFE power plant driver must be more efficient than the glass laser driver selected for the NIF. Thus, the NAS has also recommended continued development of other driver technology for defense and energy applications beyond the NIF. As an example, the DOE recently approved KD1 for the first half of the Induction Linac Systems Experiments (ILSE)[4] to demonstrate the feasibility of heavy-ion accelerators as a candidate IFE driver.

This article reports a variety of potential contributions the NIF could make to the development of IFE, drawn from a nationally attended workshop[5] held at the University of California (UC) at Berkeley in February 1994. In addition to demonstrating fusion ignition as a fundamental basis for IFE, the findings of the workshop, summarized later in this article, are that the NIF could also provide important data for target physics and fabrication technology, for IFE target chamber phenomena such as materials responses to target emissions, and for fusion power technology-relevant tests. The NIF’s contributions to IFE in all these areas will help define the corresponding design requirements for an integrated IFE technology test facility to follow the NIF, referred to by the Fusion Policy Advisory Committee as the Engineering Test Facility (ETF).[6] In particular, tests of both direct- and indirect-drive targets on the NIF will be critical to the selection of the ETF driver and of the targets that would be compatible for the chosen ETF driver. Figure 2 shows that the NIF plays a central role in decisions for any follow-on ICF facility, including the ETF, the Laboratory Microfusion Facility (LMF),[2,7] and a possible combined ETF/LMF sharing a common driver.[8] This is true even for other driver technology options for the ETF shown in Fig. 2, since the NAS review[3] noted that the most critical target physics issues (capsule symmetry, hydrodynamic stability, and fuel mix) that would be addressed in the NIF are common to all ICF and IFE target options.

Summary of the 1994 NIF–IFE Workshop

Scope of the Workshop

Sixty-one participants from 17 U.S. organizations attended the NIF-IFE workshop convened at UC Berkeley on February 22–24, 1994. The participants were briefed on the NIF laser and target area experimental capabilities, and then were asked to identify possible experimental approaches for the NIF to address critical IFE issues apart from driver development (since drivers other than the glass laser type used by the NIF will be developed for IFE). Nondriver-specific IFE issues in the areas of target physics, fusion chambers, fusion power technology, and target technology were drawn from recent power plant studies.[9–11] Rather than test specific IFE power plant designs, the NIF experiments will be used to provide data to improve understanding of generic target and fusion chamber physics and technologies relevant to IFE. Then, by experimentally benchmarking various design codes using the NIF data, those codes could be applied to many specific designs for future IFE power plants and for defining corresponding tests in the ETF following the NIF.

The workshop participants considered possible NIF contributions in four IFE areas: target physics, target chamber dynamics, fusion power technology, and target systems. Examples in each of these areas will be discussed in the following sections. The participants considered experiments that were generally consistent with the flexibility of the NIF conceptual design.[1] However, recognizing the preliminary nature of the proposed IFE experiments, the participants recommended more detailed designs of these experiments to adapt them to the NIF target chamber design, and to define IFE development needs prior to the possible fielding of such experiments in the NIF.

IFE Target Physics Experiments

Many of the most important target physics issues for IFE will be addressed by the planned experiments on the NIF for ICF ignition and defense sciences, using the flexibility of the NIF laser system. Each of the 192 beamlets amplify independent light input pulses, allowing significant flexibility to produce variable pulse shapes up to 20 ns and in different illumination geometries, including both direct- and indirect-drive capabilities. Figures 3 and 4 show two possible configurations of the NIF target area for indirect- and direct-drive experiments, along with some schematic examples of targets that might be tested in each beam configuration. For example, in Fig. 3, the indirect-drive target is relevant to heavy-ion IFE concepts,[11] and in Fig. 4, the direct-drive target shown is relevant to Fast Ignitor[12] and Diode-Pumped Solid State Laser[13] IFE options. Figure 4 also shows another target using the direct-drive NIF laser beam configuration that could simulate indirect-drive light-ion-type targets. The NIF ignition target physics program will explore a range of target yields and gain, studying capsule implosion characteristics and symmetry requirements, and capsule ignition and burn physics. In parallel with this effort, there will be development and benchmarking of ICF theoretical models and simulation codes also needed for the understanding of target physics requirements for IFE with laser as well as other drivers, and for direct-drive as well as indirect-drive targets.

Beyond the target physics experiments planned for the initial ignition campaign for ICF and defense applications, NIF can also perform experiments to explore target physics issues specific to IFE. Table 1 lists IFE target physics issues for generic ion and laser drivers, and for direct- and indirect-drive illumination geometries. The spaces marked with an “X” in Table 1 list those target physics issues that could be largely resolved using the NIF capabilities; the NIF can resolve most IFE target physics issues. The Omega Upgrade, PBFA II, and other ICF facilities around the world will be able to address the remaining issues. The completion of these experiments will provide the target physics basis to proceed with an ETF.

Figure 5(a) shows a typical indirect-drive target for IFE using heavy-ion drivers, compared with a typical target planned for the NIF ignition tests shown in Fig. 5(b). The heavy-ion IFE target in Fig. 5(a) is based on the work of Ho and Tabak.[14] The driver energies, target

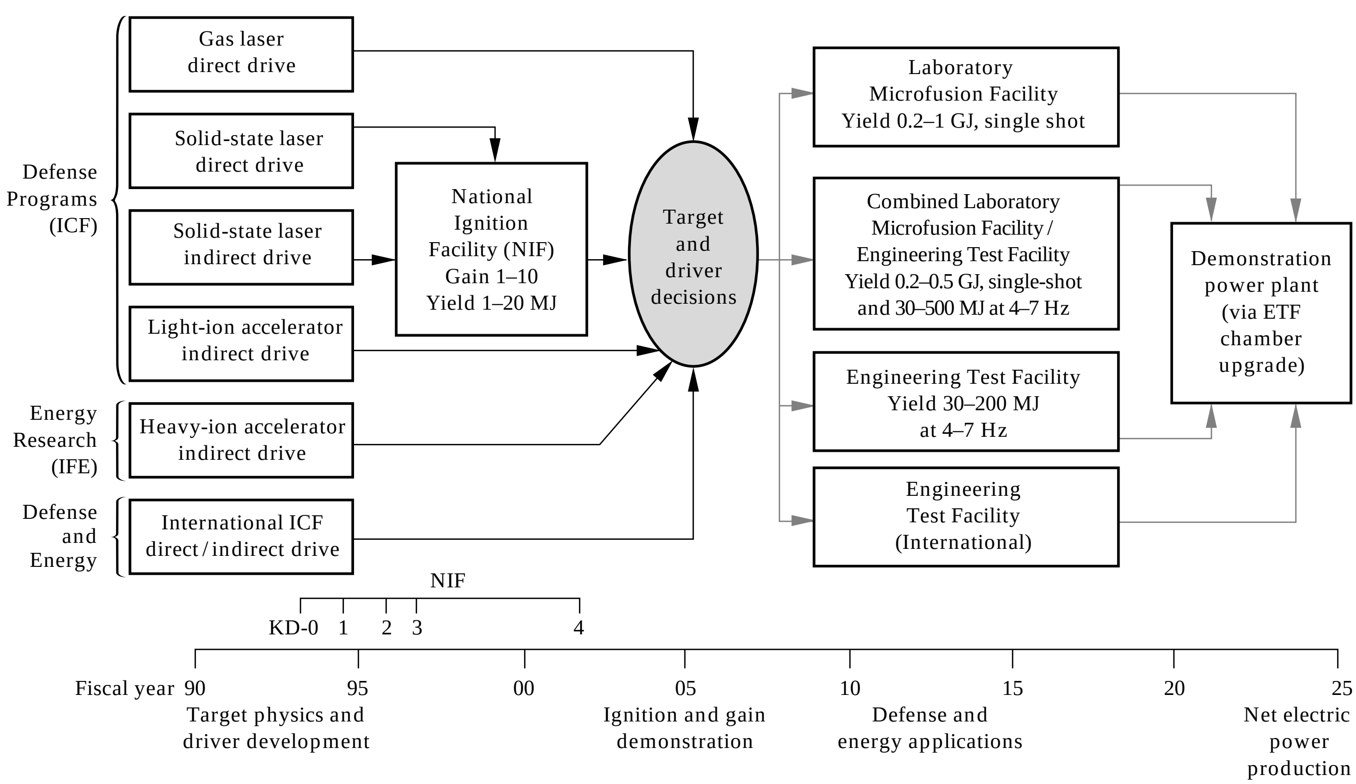


FIGURE 2. The national ICF / IFE program strategy. The NIF provides data critical to driver and target decisions for the ETF facility options, providing integrated IFE technology development. Development of a suitable chamber technology in the ETF, by upgrading one of the ETF chambers to a accommodate a higher average fusion power, can lead to a demonstration power plant by 2025. Gray lines indicate an optional path. (05-00-0295-0387pb01)

fusion yields, capsule convergence ratios, in-flight aspect ratios, capsule implosion speed, maximum compressed fuel density, and maximum hohlraum temperatures for each case are compared in the table immediately below the target cross sections [Fig. 5(a)]. The comparison shows that the NIF targets will achieve target parameters either comparable to, or more challenging than, those required for the IFE target.

Target Chamber Dynamics Experiments

Three of the basic target chamber dynamics issues of IFE identified from past IFE power plant conceptual design studies[9–11] that can be addressed on the NIF are (1) characterization of IFE target soft x-ray and debris emissions, (2) the response of first-wall materials and protective wall fluids to those target emissions, and (3) the subsequent gas dynamics of the vapor blow-off in chamber clearing, vapor condensation, and vacuum recovery. The NIF has a larger laser energy than the existing Nova laser at LLNL, so that tests of the above three issues are possible on material samples large enough to exhibit temporal and spatial scales more relevant to IFE, and at energy fluxes representative of a power plant. A typical NIF target output at a full target yield of 20 MJ will put ~48 J/cm^2 of soft x rays and target debris plasma on surfaces ~1 m away from the target, similar to the deposition from 350-MJ yields on walls ~4 m away in an IFE power plant target chamber. Thus, the NIF can provide a reduced-scale test chamber environment representative of an IFE power plant for a limited number of shots. There are also a number of one- and two-dimensional (1- and 2-D) hydrodynamics and radiation-hydrodynamics codes that could be calibrated and improved with NIF chamber dynamics data, including CONRAD,[15] HYADES,[16] SRIPUFF,[17] L2D,[18] PHD-4,[19] and TSUNAMI.[19] To acquire the data needed for these codes, NIF chamber dynamics experiments will need new diagnostics to measure the ion velocities (energies), species, and flux originating from targets, and modest improvements of existing instruments to measure gas dynamics and condensation phenomena (such as fast-response pressure transducer arrays).

Figure 6 shows an example of a possible NIF experiment designed to test the predictions of a chamber dynamics code such as TSUNAMI. The test assembly consists of a conical chamber in which a test material at the back surface is ablated by x rays that are admitted through a hole in the larger front plate. The conical shape will provide a better test of the 2-D modeling capability of the codes than would a cylindrical chamber. The high fluences attainable on the NIF will permit the use of a relatively long chamber (for longer time-scale gas dynamics) while still providing a large amount of ablated vapor from the rear surface.

The table in Fig. 6 immediately below the drawing shows how this NIF experiment is a relevant test to IFE first-wall designs (OSIRIS, HYLIFE-II and CASCADE),

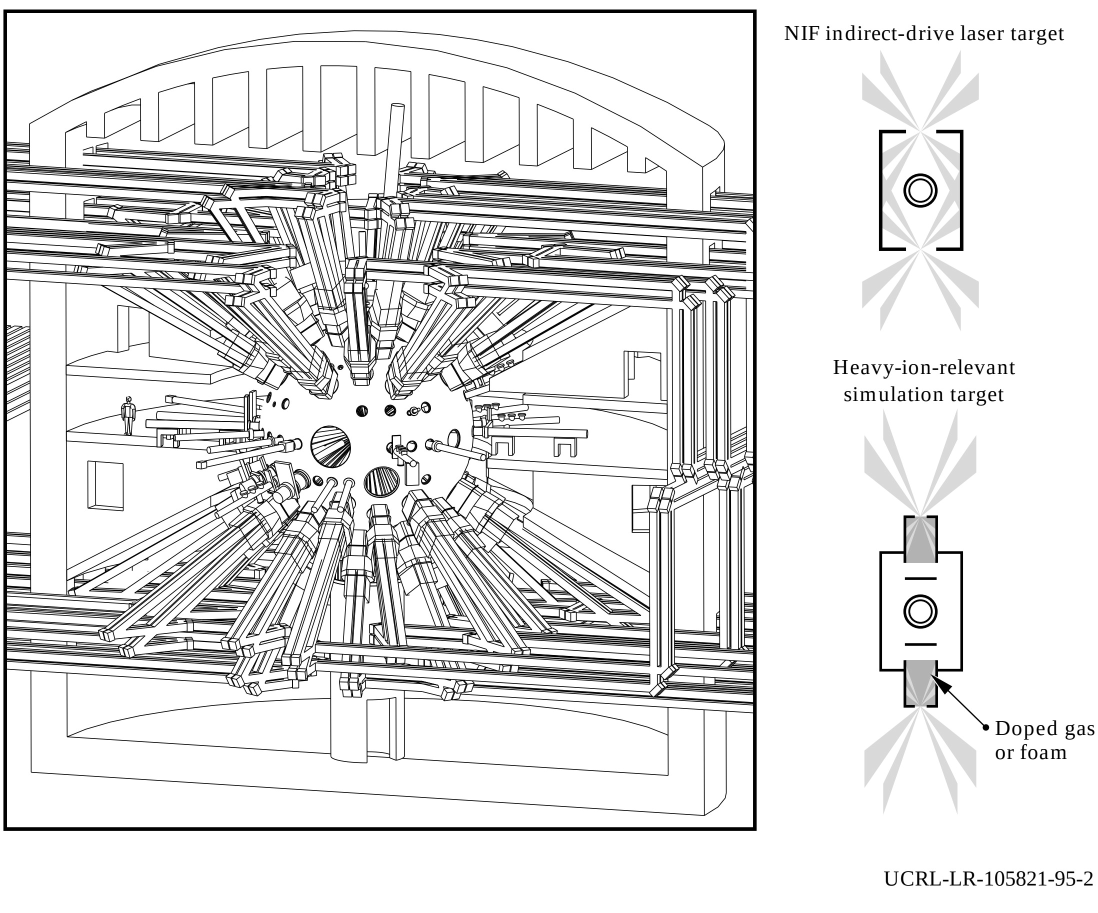


FIGURE 3. The 192 beams of the NIF configured for indirect-drive are distributed around two pairs of cones with a vertical axis of symmetry. Examples of indirect-drive targets are shown on the right. (40-00-0894-3299pb01)

in the areas of x-ray fluence, ablation depth, and time scale for the ablation of material. Passage of the expanding vapor is recorded by pressure transducers placed along the length of the cone. This information will enable the confirmation of model predictions of velocities and shock reflection strengths (from the plate at the large end of the cone). The experiment will also allow estimates of condensation rates to be obtained from the reduction in pressures at later times. Distribution of condensed material will be determined from post-shot analysis of the cone's inner surface. Examination of the ablated disk after the shot will determine the amount of material ablated, an important input parameter for the gas dynamics calculations.

Fusion Power Technology Experiments

Fusion power technology (FPT) in an IFE power plant includes components whose primary functions are energy conversion, tritium production and processing, and radiation shielding. The dominant issues for FPT in IFE power plants involve the nuclear and material

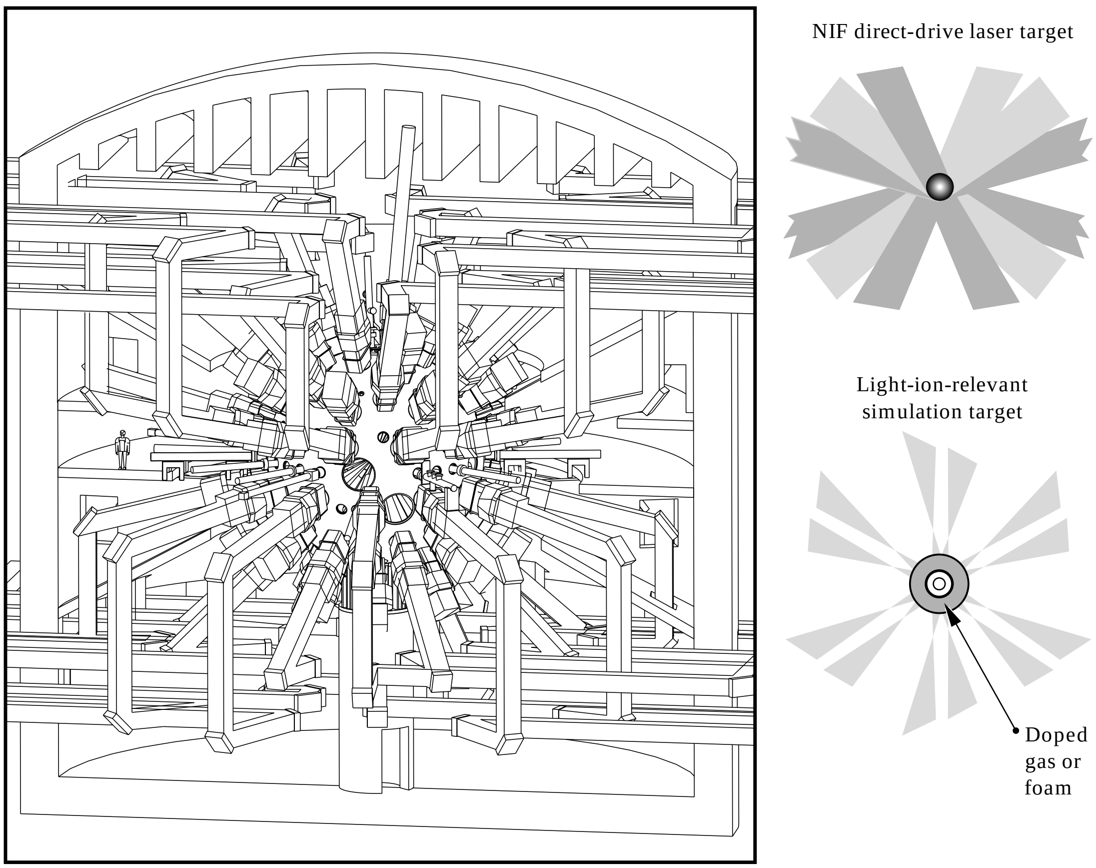


FIGURE 4. By moving 24 final beam optics assemblies to the equatorial plane and repointing each beam, direct-drive experiments with beam clusters illuminating the capsule on 48 spherically symmetric points can be performed. The light-ion simulation target is a potential indirect-drive target using a doped-foam soft-x-ray converter, but uses the NIF direct-drive-illumination configuration for symmetry reasons. (40-00-0894-3299pb02)

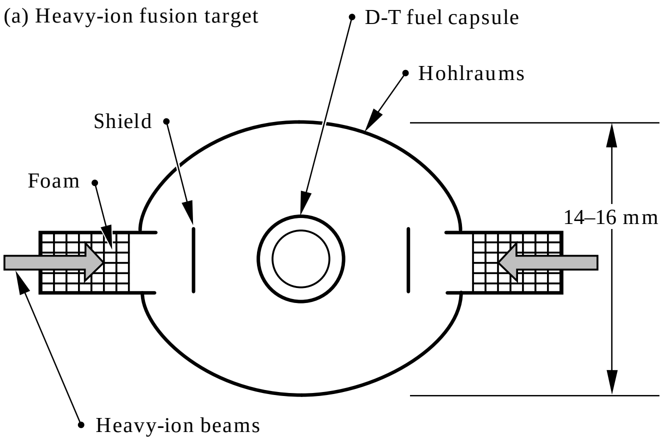
TABLE 1. IFE target physics issues for ion and laser drivers, direct and indirect drive. An "X" indicates issues that can be largely resolved with the NIF capabilities.

	Ion drivers		Laser drivers	
	Indirect	Direct	Indirect	Direct
Usability of a variety of pulse shapes	X	X	X	X
Radiation flow, illumination geometry, and internal pulse shaping	X		X	X
Sensitivity of capsules to radiation asymmetry	X		X	X
Materials issues (capsule, hohlraum, ablator)	X	X	X	X
Fabrication surface finish and precision	X	X	X	X
Capsule mounting and injection	X		X	X
Power vs energy trade-offs	X		X	X
Output spectra and shielding	X	X	X	X
Reduced tritium	X	X	X	X
Advanced targets	X	X	X	X

performance of components so as to achieve economic competitiveness and to realize safety and environmental advantages. The NIF will provide valuable information to IFE FPT, both with the demonstrated performance and operation of the basic facility itself and with data obtained from experiments designed specifically to test FPT issues. The NIF's relevance to FPT is in its prototypical size and configuration and its prototypical radiation field (neutrons, x rays, debris) spectra and intensity per shot. The most important limitation of the NIF for FPT experiments is the low repetition rate (low neutron fluence). The most important contributions of NIF to FPT development for IFE are the following:

1. Fusion ignition.
2. Design, construction, and operation of the NIF (integration of many prototypical IFE subsystems.
3. Viability of first-wall protection schemes.
4. Dose rate effects on radiation damage in materials.
5. Data on tritium burnup fractions in the target, some important tritium inventory and flow rate parameters, and data on achievable tritium breeding rate in samples.
6. Neutronics data on radioactivity, nuclear heating and radiation shielding.

Figure 7 depicts an example of a possible NIF experiment addressing item 3: a NIF experiment to study the recovery of a protective liquid metal film flow following the effects of pulsed heating by the target output of soft x rays, target plasma debris, and neutrons, analogous to the first-wall protective film invoked in the Prometheus study.[10] In addition to soft x rays and target debris, the NIF target would generate 10^{19} 14-MeV neutrons / shot, sufficient to test liquid jet breakup at 25 to 50 cm distance due to isochoric neutron heating representative of the liquid-wall HYLIFE-II IFE concept.[12]



	Heavy-ion fusion target	NIF target
Driver energy (MJ)	4 to 6	1.8
Yield (MJ)	300 to 450	15
Convergence ratio	27	36
In-flight aspect ratio	40	45
Imploded speed (cm / µs)	32	41
Max density ρ (kg / m^3)	6.5×10^5	1.2×10^6
Max hohlraum temp (eV)	260	300

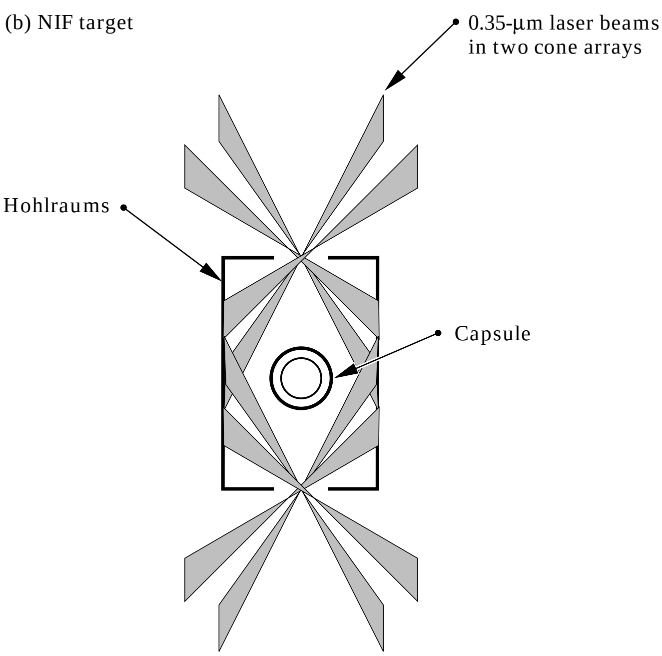
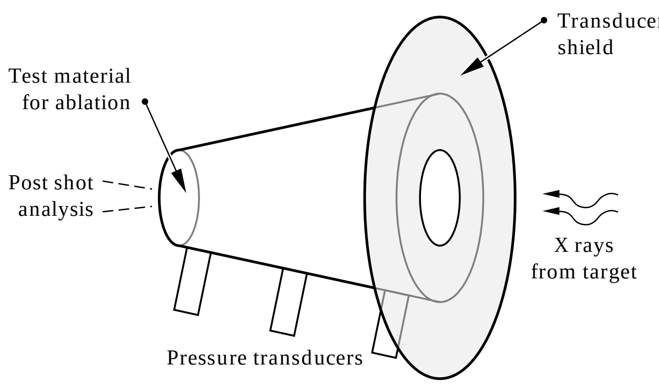


FIGURE 5. Key target parameters compared between (a) a heavy-ion target design for an IFE power plant, shown in schematic views, and (b) a typical NIF ignition target. (70-37-0894-3150pb04)



	NIF experiment	IFE first wall		
		OSIRIS	HYLIFE-II	CASCADE
X-ray fluence at radius	200 J / cm^2 0.4 m	60 J / cm^2 3.5 m	2000 J / cm^2 0.5 m	60 J / cm^2 3.1 m
Ablation	20 µm	20 µm	200 µm	3 µm
Time scale	40 µs	100 µs	50 µs	90 µs

FIGURE 6. An experiment on the NIF to calibrate gas dynamic codes. The x-ray fluence, ablation depths, and time scales for the NIF experiment shown are comparable to many cases of interest in IFE first-wall concepts. Where the parameters differ, the NIF experiments can still be useful to calibrate the computational model. (05-00-0894-3048pb02)

One of the more unique features the NIF can provide is a very high dose rate in each shot that can be equivalent to 10–1000 displacements per atom per second. Even with single shot operation, the NIF will be useful for basic physics of radiation effects in materials. Examples include cascades (morphology, size, fraction of free and clustered defects, impurities), microstructural evaluation, electrical properties, optical properties (fiber optics, coatings), and molecular cross linking. In some low-activation materials like SiC, we predict that such a large number of damage sites can be produced in each pulse that the collection of interstitial atoms produced from one damage site can combine with the vacancies created not only at that site, but also from nearby sites. This would lead to higher recombination rates of interstitial atoms with vacancies than the steady-state situation. The very high neutron dose rates provided by the NIF allow these dose rate effects to be tested.

One predictive technique that can calculate and interpret material responses to NIF neutron damage is called Molecular Dynamic Simulation (MDS).[20] MDS calculates responses at an atomic level by quantifying the response of a 3-D matrix of atoms to so-called “knock-on” atoms that impinge on the matrix from a range of angles and with a range of energies, as would result from an incident neutron flux. Potentially, MDS capabilities include predicting for a material the number of vacancies and interstitials that will result from a neutron irradiation pulse, the cluster fraction of defects, atomic mixing and solute precipitation, and phase transformations.

IFE Target Systems

The workshop separated IFE target systems topics into three broad areas: IFE target fabrication, IFE target transport, and IFE target systems. The following subsections discuss each of these areas, including some of the issues that must be resolved to successfully develop an IFE power plant, and examples of experiments that could be done in the NIF to help resolve these issues.

IFE Target Fabrication

IFE target fabrication includes target materials and configuration selection, capsule production, hohlraum production, target assembly, characterization, fill, and layering. The targets that fuel an inertial fusion power plant based upon the indirect-drive approach will be similar to the ignition and high-gain targets developed for the NIF. There are differences, however. The IFE fuel capsules will be two to three times larger in diameter. For a laser driver, hohlraums will scale similarly, but ion targets will require substantially different hohlraums and x-ray converters. As with NIF high-gain targets, IFE targets will be cryogenic. The major issues associated with developing these targets, broadly stated, are (1) assuring the target component quality specifications as sizes increase and fabrication techniques change; (2) assuring a fast enough fuel fill rate to be able to maintain the plant’s tritium inventory at acceptable levels; and (3) developing fabrication and inspection techniques that produce high-quality, economically viable targets. A fourth issue, dealt with in the section below on target transport, is providing targets that can

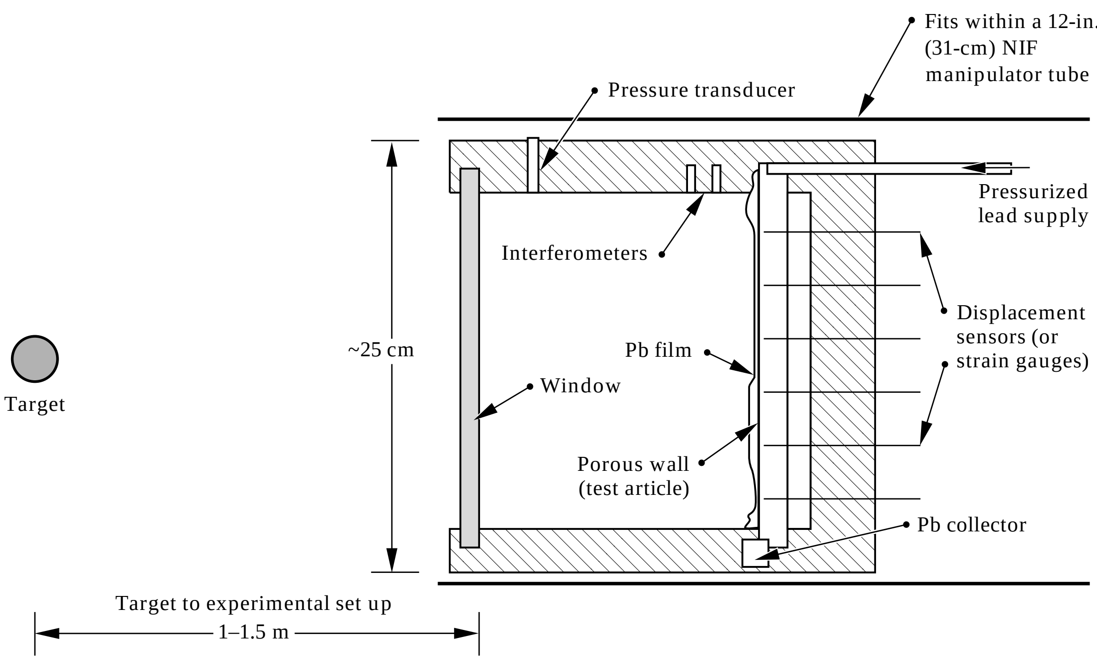


FIGURE 7. Example of a protective liquid metal film flow experiment on the NIF (not drawn to scale). The debris window might be removed to study effects of soft x rays and debris separately. (05-00-0295-0386pb01)

withstand the accelerations attending chamber injection and that can withstand the chamber environment once injected.

Table 2 lists more fine-grained issues that must ultimately be addressed to produce and use IFE targets, and an assessment of the importance of the NIF in developing solutions. Those that require full scaling to IFE sizes, such as the effect of cryogenic layer quality on gain, cannot be completely tested to ignition on the NIF. Those that do not require such scaling, such as materials choices and automated cryogenic assembly techniques, should be tested on the NIF. The NIF would be a unique test bed, since the relevant test of success is ignition.

IFE Target Transport

Under the category of target transport, we include both transport from the target fabrication facility to the target injector and the injection of the target to the point of ignition. Completed targets will be stored in a cryogenic storage system prior to transport to the injector and must be kept at constant temperature throughout the entire transport and injection process. Even after the target leaves the injector and enters the chamber environment, the allowed temperature rise of the cryogenic fuel is very low, estimated to be less than 0.2 K. Targets must also survive the acceleration process. The target transport issues for IFE are listed in Table 2. As indicated, the NIF will be useful for addressing many of these issues.

IFE Target Systems

Target fabrication and injection systems for IFE will require developments listed in Table 3. For each target development activity, Table 3 indicates whether the development is needed for the ICF ignition campaign as well as for IFE ("Needed for NIF"), needed specifically for IFE and able to be tested in the NIF ("Needed for NIF–IFE experiments"), or needed specifically for IFE beyond that which is to be tested in the NIF ("Needed for IFE"). The last column on the right in Table 3 indicates, where applicable, in which ongoing ICF program each target development activity would be included. The label "B—target fabrication development activity" indicates that the activity would be included as part of the present ICF base program for development on noncryogenic targets, and the label "D—National Cryogenic Target (R&D) Research and Development Program" indicates the activity would be part of the ICF Program to develop smooth DT cryolayer targets, initially for the Omega Upgrade direct-drive tests and later for the NIF. Some of the target fabrication issues must be faced early to field ignition targets on the NIF and will require continuation and expansion of current

TABLE 2. IFE target fabrication and target transport issues.

	NIF usefulness*	NIF uniqueness**
Target Fabrication		
Low-cost mass-production techniques for capsules and their effect on quality, materials choice and gain	2	3
Low-cost mass production techniques for laser driver hohlraums	2	3
The effect of cryogenic layer quality on gain	2	3
Automated cryogenic assembly techniques	3	3
Fast fill techniques for low tritium inventory	2	3
High-throughput quality inspection techniques	2	3
Target Transport		
Injection techniques for high-rep-rate cryogenic operation	0	1
Time and space accuracy and sensing	0	1
Integration	2	1–2
Target survival under acceleration	2	3
Thermal protection and temperature control	2	2
Chamber environment effects on trajectory	1–2	3
Demonstration of high-rep-rate operation	2	3

* Usefulness: 3 = complete resolution; 2 = partial resolution; 1 = useful information; 0 = no use.
**Uniqueness: 3 = NIF unique and required; 2 = NIF not unique but could be used; 1 = issues addressed better or cheaper in new facility; 0 = issues addressed better or cheaper in existing facility.

target development activities. The proposed testing in the NIF of IFE-relevant targets will require that those targets first be developed. Relatively little has been done in that area to date, and the workshop recommended a program of target design and fabrication R&D to have prototypical IFE targets ready for testing on the NIF. This testing will come after the NIF primary mission of ignition has been achieved, which is about 5 yr after the startup of the NIF.

Cryogenic ignition experiments on the NIF will require cryogenic target transport systems. Development of these systems will benefit greatly from work on similar systems being developed for OMEGA Upgrade. IFE will require sophisticated target injection and tracking systems that have yet to be seriously studied. IFE target experiments on the NIF will require that a portion of the development needed on these systems be done. The workshop recommended that IFE tracking and pointing studies be done now to define the systems that could be tested on the NIF, followed by development of the required hardware for these experiments. These experiments would logically follow the static tests of IFE prototype targets described above.

The NIF can provide integrated performance tests of candidate IFE targets as a function of reduced precision and manufacture cost. A series of non-ignited model targets could be injected in a 5-Hz burst, by stagger-firing 2–4 groups of laser chains ~100 ms apart, to test the repeatability of beam-target engagement accuracy in a multishot chamber environment. Since each of the 192 beamlets of the NIF can be fired separately, this type of experiment should be possible. It would also be useful to conduct experiments where uniform illumination of a target could be obtained using only a fraction (e.g., 1/4 or 3/4) of the beams.

Conclusions

The role of the NIF can uniquely cover a large and essential portion of needed IFE development in four areas.

1. IFE target physics and design/performance optimization. NIF target physics experiments with both direct and indirect drive will give us the data needed to predict the minimum driver energy, power, pulse shape and symmetry requirements for a variety of potential IFE drivers and targets.

TABLE 3. IFE target systems R&D needs.

Development Item	Needed for: NIF	NIF–IFE experiments	IFE	Current R&D activity*
Target Fabrication				
Targets for Ignition				
Ignition target design	X			A
1–3-mm capsules	X	X	X	B
High-pressure DT fill and condensation	X	X	X	C
Cryogenic layering	X	X	X	D
Cryogenic characterization	X	X	X	D
Cryogenic assembly	X	X	X	—
Targets for IFE				
IFE target design	X	X	—	
IFE target fabrication		X	X	—
Cost-effective fabrication			X	—
Target Transport				
Transport Systems				
Transport to reaction chamber	X	X	X	C
High through-put transport			X	—
Injection and Tracking				
Stationary mounting system	X	X		C
Free-fall injection	X		—	
High-speed injection		X	X	—
High-rep-rate, rad-hardened injection			X	—
Target tracking	X	X	—	
Hardened target tracking			X	—

*A = NIF design activity; B = target fabrication development activity; C = OMEGA Upgrade design; D = National Cryogenic Target Research and Development Program.

2. IFE fusion chamber dynamics and first-wall response. Using the output of ignited targets, NIF experiments will be able to characterize radiation, shock, and debris effects on various first-wall candidates and on driver / reactor interface systems, providing the data necessary to design multiple pulse and high-rep-rate experiments for the ETF.
3. IFE fusion power technology, materials science and safety. NIF experiments will be essential for calibrating and improving the predictive capabilities of x-ray, debris, and neutron emissions and their effects on tritium handling, nuclear heating, materials, and safety and the environment. The NIF facility will be prototypical of future IFE power plants in these areas.
4. IFE target systems tests of precision and performance of mass-fabricated IFE targets and high-rep-rate target-injection systems. NIF experiments can study the target manufacturing tolerances required for mass production and the positioning requirements of the injection, tracking, and beam pointing systems.

In conclusion, the NIF will be a centrally important experimental facility to support a broad range of research on the IFE development path.

Acknowledgments

The author would like to acknowledge the contributions of the 61 participants who attended the workshop at UC Berkeley on February 22–24, 1994, who provided many of the ideas forming the basis of this article. In particular, thanks go to Mike Tobin, who was a key and tireless organizer of the NIF–IFE workshop and who provided much of the written output of this workshop from which much of the article was drawn.

Notes and References

1. J. A. Paisner, *National Ignition Facility Conceptual Design Report—Executive Summary*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-PROP-117093 ES (1994).
2. *Inertial Confinement Fusion Five-Year Program Plan FY 1992–FY 1996*, DOE Office of Research and Inertial Confinement Fusion, Washington D.C., 20585, Dec. 31, 1991 (revised March 1993).
3. National Research Council, *Second Review of the Department of Energy's Inertial Confinement Fusion Program, Final Report*, (National Academy Press, Washington, D.C., 1990).
4. "Findings and Recommendations for the Heavy-Ion Fusion Program," *Report of the Fusion Energy Advisory Committee (FEAC) to DOE Energy Research Director William Happer*, DOE Office of Fusion Energy, ER-50, Germantown, Washington D.C., 20545 (April 1993).
5. B. G. Logan et al., "Utility of the U.S. National Ignition Facility for Development of Inertial Fusion Energy," *Proc. of 15th IAEA Int. Conf. on Plasma Physics and Controlled Fusion Research*, paper IAEA-CN-60 / B-P-15, Seville, Spain, Sep 26–Oct. 1 (1994).
6. Fusion Policy Advisory Committee, *Review of the U.S. Fusion Program, Final Report*, DOE Office of Energy Research, Washington, D.C., 20585 (1990).
7. *The Laboratory Microfusion Capability Study Phase II Report*, DOE Office of Inertial Confinement Fusion, DOE Office of Research and Inertial Confinement Fusion, Washington D. C, 20585, DOE / DP-0017, May 1993.
8. C. L. Olson, R. O. Bangerter, B. G. Logan, and J. D. Lindl, "ICF Driver Strategies for IFE," *Proc. of the IAEA Technical Committee Meeting on Drivers for ICF*, Paris, France, Nov. 14–18 (1994).
9. W. R. Meier (Ed.), "OSIRIS and SOMBRERO Inertial Fusion Power Plant Designs—Final Report, " W. J. Schafer Associates, DOE Office of Fusion Energy, ER-50, Germantown, Washington D.C., 20545, W. J. Schafer Associates Report WJSA-92-01, DOE Report DOE / ER / 54100-1 (1992).
10. L. M. Waganer (Ed.), "Inertial Fusion Energy Reactor Design Studies—Prometheus-L and Prometheus-H," McDonnell Douglas, DOE Office of Fusion Energy, ER-50, Germantown, Washington D.C., 20545, McDonnell Douglas Report MDC 92E0008, DOE Report DOE / ER-54101 (1992).
11. R. W. Moir et al., *Fusion Technology* 25, 5–25 (1994).
12. M. Tabak et al., "Ignition and High Gain with Ultra-Powerful Lasers," prepared for *Nov. 1993 APS Division of Plasma Physics*; *Physics of Plasmas* 1 (5) (1994).
13. C. D. Orth, S. A. Payne, and W. F. Krupke, "A Diode-Pumped Solid-State Laser Driver for Inertial Fusion Energy," Lawrence Livermore National Laboratory preprint UCRL-JC-116173 (1994) (to be published).
14. D. D.-M. Ho and M. Tabak, *Proc. of 15th IAEA Int. Conf. on Plasma Physics and Controlled Fusion Research*, paper IAEA-CN-60 / B-P-13, Seville, Spain, Sep. 26–Oct. 1. (Lawrence Livermore National Laboratory private communication: Tabak suggested the concept of using dense gas radiators for NIF–HIF model targets, 1994.)
15. R. R Peterson, J. J. Macfarlane, and G. A. Moses, "CONRAD—a combined hydrodynamic-condensation / vaporization computer code," University of Wisconsin Fusion Technology Institute, 1500 Johnson Dr., University of Wisconsin, Madison, WI, 53706, UWFDM-670 (1980).
16. J. Larsen, Cascade Applied Sciences Inc. code (licensed), version 01.05.04 (1992).
17. L. Seaman and D. Curran, *SRIPUFF—Final Report*, SRI Int., Poulter Laboratory, Stanford Research Institute, Menlo Park, CA, 2 (1980).
18. T. Cooper, *A Computer Code for Numerical Simulation of Shock Waves in Fluids and Solids*, Swedish Detonic Research Foundation, Report No. DS 1980:16 (1980).
19. J. C. Liu et. al., *Fusion Technology* 21, 1514–1519 (1992).
20. J. Wong et al., "The Threshold Energy for Defect Production in SIC: A Molecular Dynamics Study," Lawrence Livermore National Laboratory, Livermore, CA, UCRL-JC-114789 (1993). Also see *Proc. of the 6th Int. Conf. on Fusion Reactor Mat.*, Stresa, Italy (1993).